Gravity of the New Madrid Seismic Zone—A Preliminary Study

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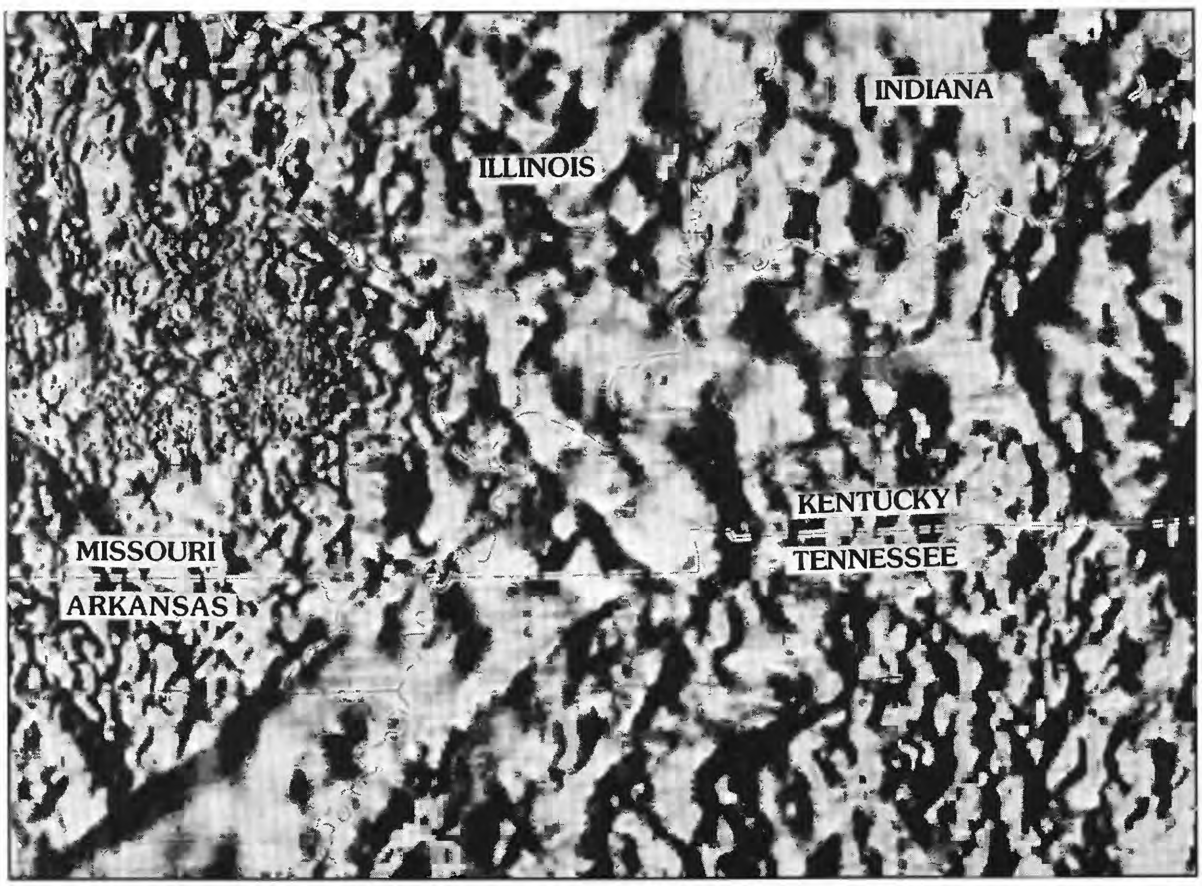

Cover. Gray, shaded-relief map of magnetic anomaly data. Map area includes parts of Missouri, Illinois, Indiana, Kentucky, Tennessee, and Arkansas. Illumination is from the west. Figure is from *Geophysical setting of the Reelfoot rift and relations between rift structures and the New Madrid seismic zone*, by Thomas G. Hildenbrand and John D. Hendricks (chapter E in this series).

Gravity of the New Madrid Seismic Zone—A Preliminary Study

By V.E. Langenheim

INVESTIGATIONS OF THE NEW MADRID SEISMIC ZONE
Edited by Kaye M. Shedlock *and* Arch C. Johnston

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GRAVITY OF THE NEW MADRID SEISMIC ZONE—A PRELIMINARY STUDY

By V.E. Langenheim

ABSTRACT

The gravity field over the northern Mississippi Embayment indicates no vertical offsets of the unconformity between Paleozoic and Cretaceous rocks of greater than 0.25 km. Using the maximum-horizontal-gravity-gradient method, it is possible to locate density boundaries within the subsurface that delineate small, post-Cretaceous faults or igneous intrusions. Detailed gravity profiles display small-amplitude (less than 2 mGal), short-wavelength anomalies that are caused by shallow sources (less than 1 km deep). These anomalies may result from density variations caused by (1) post-Cretaceous faults, (2) igneous bodies, or (3) fill in ancient stream channels. Specific sources for these anomalies can be distinguished by the anomaly shape (linearity, amplitude, width), as well as by using other geophysical data (e.g., magnetic and seismic data).

INTRODUCTION

Three devastating earthquakes shook the northern Mississippi Embayment in the winter of 1811 and 1812, destroying the town of New Madrid, Mo. (Nuttli, 1973). The New Madrid area is currently the most seismically active region of the Central and Eastern United States. Because Tertiary and Cretaceous sedimentary rocks and unconsolidated Quaternary sediments cover the New Madrid seismic zone, potential-field geophysics has played a crucial role in understanding the geologic framework of the Mississippi Embayment region (Ervin and McGinnis, 1975; Hildenbrand and others, 1977, 1982; Kane and others, 1981; Hildenbrand, 1985). Potential-field studies have outlined buried plutons and an ancient rift system that play a key role in influencing the distribution of seismicity. In general, though, these previous studies have been regional in scope and have not investigated the small-amplitude, short-wavelength anomalies that result from shallow sources. Such sources may provide information on specific structures that control the release of seismic energy in the region. One of the few studies addressing these short-wavelength anomalies is the detailed gravity and ground-magnetic data collected across the Reelfoot scarp (Stearns, 1980). In this study, I discuss the gravity field over the seismically active zones in the northern Mississippi Embayment in an attempt to identify possible shallow gravity sources related to faulting over a broader area. Existing regional gravity data are filtered to enhance certain anomaly characteristics such as wavelength or trend and thus provide new interpretive information about the distribution and nature of shallow structures.

GEOLOGIC SETTING

The northern Mississippi Embayment is characterized by a broad, southwest-plunging syncline filled with unconsolidated Upper Cretaceous and Tertiary sedimentary deposits, which unconformably overlie lower Paleozoic limestone, shale, and sandstone (Stearns and Marcher, 1962). Precambrian crystalline rocks, which underlie the Paleozoic rocks and form the basement, may be equivalent to rocks exposed in the St. Francois Mountains in Missouri. The northeast-trending Reelfoot graben, imaged primarily by magnetic methods (Hildenbrand and others, 1982; Hildenbrand, 1985), developed during rifting in Precambrian or Cambrian time (fig. 1). The graben is 70 km wide, with a structural relief of about 2 km, and is flanked by several large, dense, magnetic plutons. These mafic intrusions could have formed during the Precambrian or Cambrian rifting episode or as recently as the Cretaceous during an episode of rift reactivation (Glick, 1982; Hildenbrand and others, 1982). One well has penetrated Precambrian granitic gneiss within the graben (Denison, 1984). Regional subsidence and deposition during the early Paleozoic resulted in the thick accumulation of sedimentary rocks in the Reelfoot Basin. These rocks were then uplifted and eroded to form the Pascola arch during late Paleozoic and possibly Mesozoic time (Grohskopf, 1955). Late Cretaceous subsidence and deposition of marine and

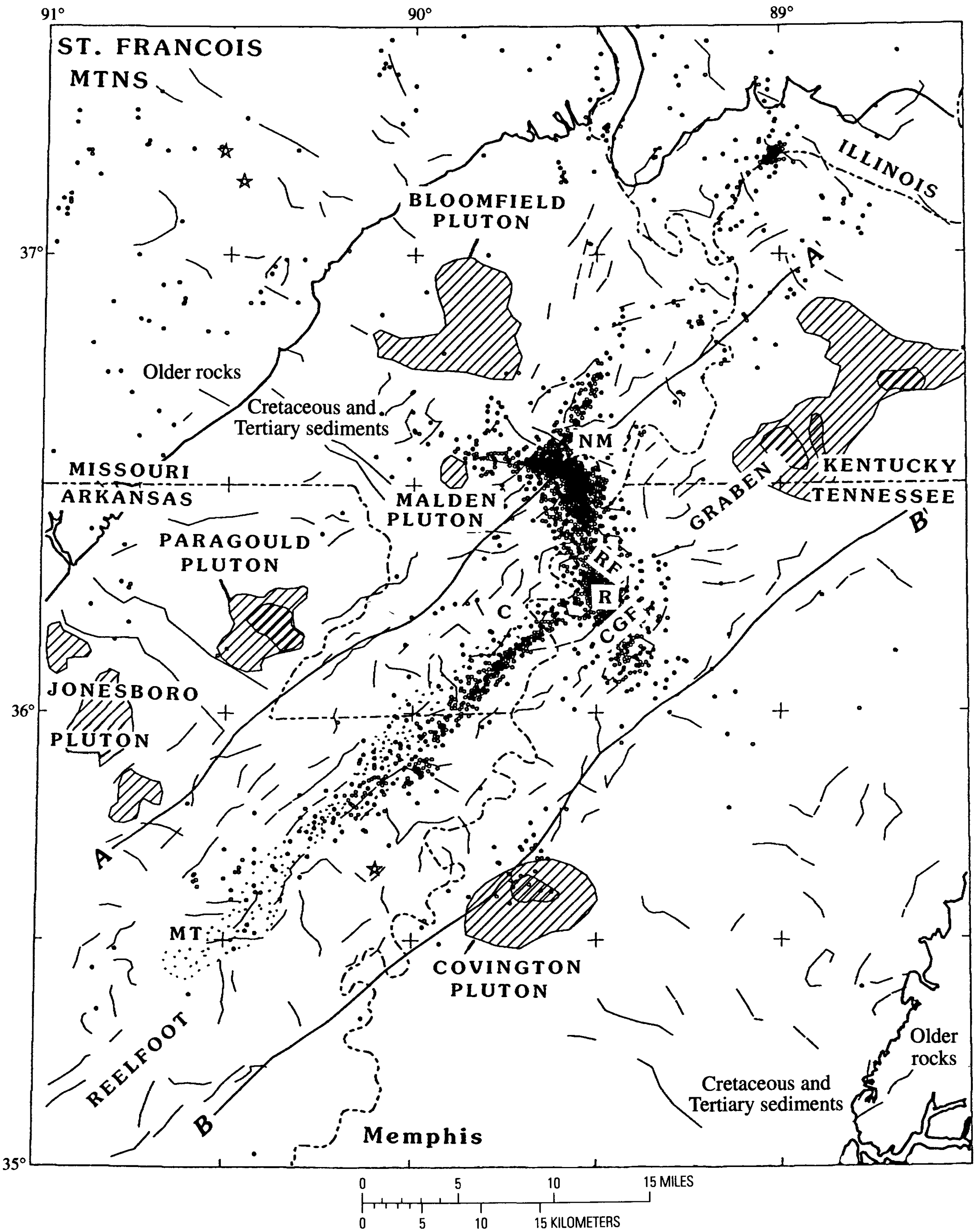


Figure 1. Map showing seismicity and inferred structures in the northern Mississippi Embayment and surrounding regions. Circles indicate earthquakes. Areas with diagonal-line pattern denote inferred mafic plutons whose boundaries are based on maximum-horizontal-gravity-gradient method. For some plutons, more than one boundary may be necessary to delineate the areal extent of the pluton (i.e., Covington). Thin lines indicate density boundaries calculated from residual gravity field. Stippled area outlines the Blytheville arch. Stars show locations of drill wells that bottomed in Precambrian basement, and lines A–A′ and B–B′ delineate the graben margins as interpreted from magnetic data (Hildenbrand and others, 1979). Thick line outlines extent of Cretaceous and Tertiary sedimentary deposits. MT, Marked Tree, Ark.; C, Caruthersville, Mo.; NM, New Madrid, Mo.; R, Ridgely, Tenn.; CGF, Cottonwood Grove fault; RF, Reelfoot fault.

nonmarine clastic sediments in the Mississippi Embayment continued during the Tertiary. These deposits are covered by a thin blanket of Quaternary fluvial deposits.

Earthquakes occur in the New Madrid seismic zone along three well-developed linear zones: (1) a northeast-trending linear zone extending from Marked Tree, Ark., to Caruthersville, Mo., (2) a north-northwest-trending zone from Ridgely, Tenn., to New Madrid, Mo., and (3) a northeast-trending zone west of New Madrid (fig. 1). Earthquakes are characterized by both right-lateral and thrust focal mechanisms (Herrmann and Canas, 1978) at depths of 3 to 14 km (Andrews and others, 1985). Seismic reflection data have revealed a major disrupted zone and antiform within the Paleozoic sedimentary sequence that coincides geographically with the Marked Tree–Caruthersville seismic zone (Howe and Thompson, 1984; Crone and others, 1985; Hamilton and McKeown, 1988). This disrupted zone, named the Blytheville arch, is about 10–15 km wide and 110 km long. Various explanations have been suggested for the origin of the disrupted zone, including felsic igneous intrusions (Crone and others, 1985), shale diapirs (McKeown and others, 1990), and fault zones (Howe and Thompson, 1984; Hamilton and McKeown, 1988). Seismic reflection data have also imaged faults that displace Upper Cretaceous and Tertiary rocks (Zoback and others, 1980; Hamilton and Zoback, 1982; Sexton and Jones, 1986), but individual faults with vertical offsets greater than 100 m have not been identified.

Using remote sensing data, Schweig and Marple (1991) have found an intriguing lineament that may be the surface expression of one of the coseismic faults of the 1811–12 New Madrid earthquakes. The Bootheel lineament is a 135-km-long zone of liquefied sand erupted through fissures, but it does not coincide exactly with any of the major trends in seismicity.

DATA

The gravity map of the New Madrid region (fig. 2) was compiled from several data sets obtained from the Defense Mapping Agency and incorporates more than 14,800 gravity stations. Within the northern Mississippi Embayment, the average station spacing is about 2 km, but gaps are present along the Mississippi River and over wildlife refuges and lakes. The data have been reduced to free-air gravity values using standard formulas (Telford and others, 1976). Bouguer, curvature, and terrain corrections were applied to the free-air value at each station to determine the complete Bouguer gravity anomalies using a standard reduction density of 2.67 g/cm^3 (Plouff, 1977). The data were edited to remove single-station anomalies and then gridded using a 1-km interval.

In order to enhance short-wavelength features due to shallow sources, the gridded data were filtered using two different techniques. The term "shallow sources" refers to rock bodies or structures that are present within the upper 3 to 4 km; "deep" refers to rock bodies that are more than 3 to 4 km deep. The first technique used the first vertical derivative of the gravity field, which suppresses longer wavelength regional trends. The method also has a physical significance in that both the force of gravity and the magnetic scalar potential are proportional to $1/r^2$, where r is the distance from the causative body. In other words, the first vertical derivative of the gravity field is equal to the magnetic field in the case where the density of the causative body is replaced in constant proportion with a magnetization of known direction (Dobrin and Savit, 1988). Except for a multiplicative constant, the first-vertical-derivative anomalies can be considered to be pseudomagnetic anomalies. A low-pass filter was then applied to the first-vertical-derivative map in order to smooth small, spotty features that are the result of noise in the data set. Figure 3 shows the first vertical derivative of the gravity field, and figure 4 shows the magnetic field. Features on these maps are discussed later.

Another method for separation of residual from regional anomalies involves subtracting the upward continuation of the gravity field from the actual data. Upward continuation is the transformation of gravity data measured on one surface to a higher surface; this operation tends to smooth the data by attenuation of short-wavelength anomalies (Dobrin and Savit, 1988). Subtraction of the upward-continued field from the original data results in high-pass-filtered, residual anomalies. Figure 5 shows the gravity field continued upward to 3 km, and figure 6 shows the residual gravity field after subtracting the upward-continued gravity field from the complete Bouguer gravity field.

To help delineate trends and gradients in the gravity field, maximum-horizontal-gradient values were calculated using a computer algorithm (Blakely and Simpson, 1986). Gradient maxima occur directly over vertical or near-vertical contacts that separate rocks of contrasting densities. These density boundaries were calculated for both the residual gravity data (fig. 6) and the upward-continued gravity (fig. 5).

To supplement the regional gravity coverage, the U.S. Geological Survey collected three detailed gravity profiles during the summer of 1990 near preexisting seismic reflection lines (fig. 7). The data were collected with a LaCoste and Romberg gravimeter at 300- to 600-m intervals using surveyed elevations and locations, although spacing may be greater locally because of access problems (i.e., the Mississippi River). The observed gravity values were referenced to the IGSN71 datum as described by Morelli (1974) and were then reduced to complete Bouguer anomaly values using standard formulas (Telford and others, 1976). No regional correction has been applied to the data. The measurements are considered accurate to 0.2 mGal.

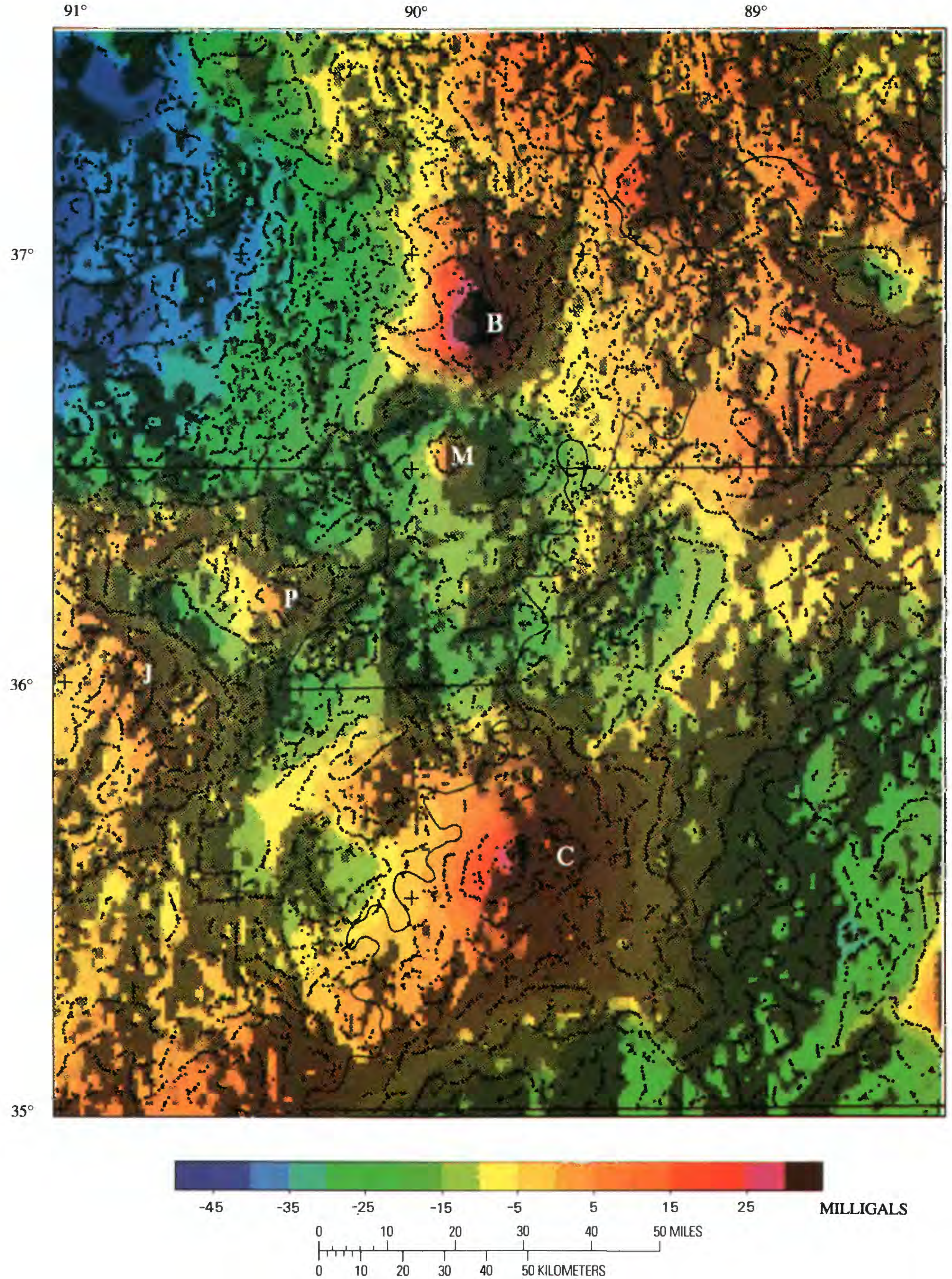


Figure 2. Shaded-relief map of complete Bouguer gravity of the northern Mississippi Embayment. Illumination is from the west. Contour interval is 5 mGal. Dots indicate positions of maximum horizontal gravity gradient (density boundaries). B, Bloomfield pluton; C, Covington pluton; J, Jonesboro pluton; M, Malden pluton; P, Paragould pluton. State boundaries are shown as solid lines.

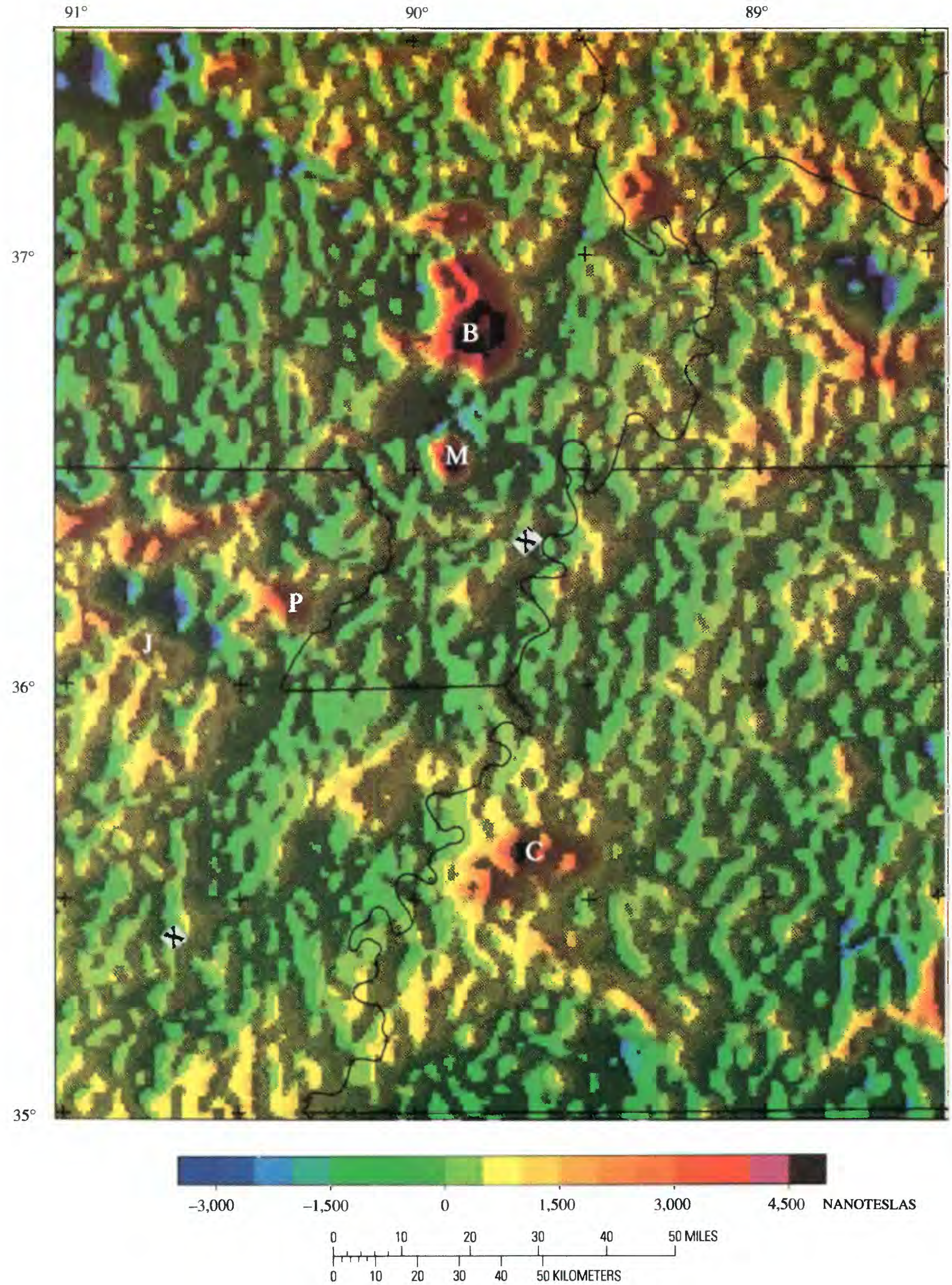


Figure 3. Pseudomagnetic shaded-relief map of the northern Mississippi Embayment computed from Bouguer gravity map. Illumination is from the west. Contour interval is 500 nT. Shading process enhances subtle structures as well as limitations in the quality of the data. B, Bloomfield pluton; C, Covington pluton; J, Jonesboro pluton; M, Malden pluton; P, Paragould pluton. X–X' marks a narrow, discontinuous high along the center of the Reelfoot rift. State boundaries are shown as solid lines.

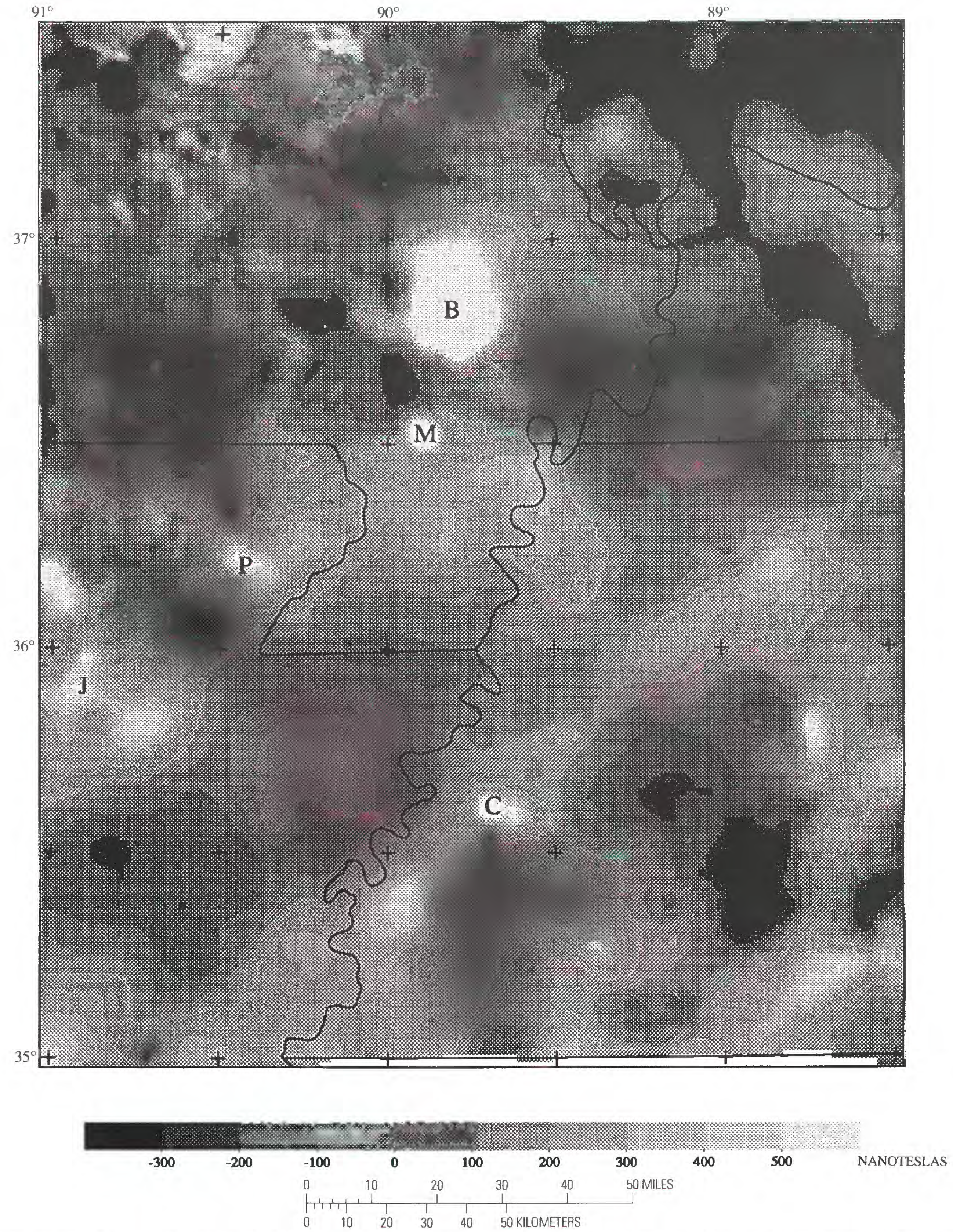


Figure 4. Magnetic field map of the northern Mississippi Embayment. Contour interval is 50 nT. Merged survey at 1,000 ft above ground (Hildenbrand and others, 1979). Magnetic data have been reduced to the pole, assuming the direction of the total magnetization vector of 66° N. inclination and 1.5° E. declination. The area of the Reelfoot graben is depicted by the belt of relatively smooth magnetic field that trends northeast across the map between plutons P and C. B, Bloomfield pluton; C, Covington pluton; J, Jonesboro pluton; M, Malden pluton; P, Paragould pluton. State boundaries are shown as solid lines.

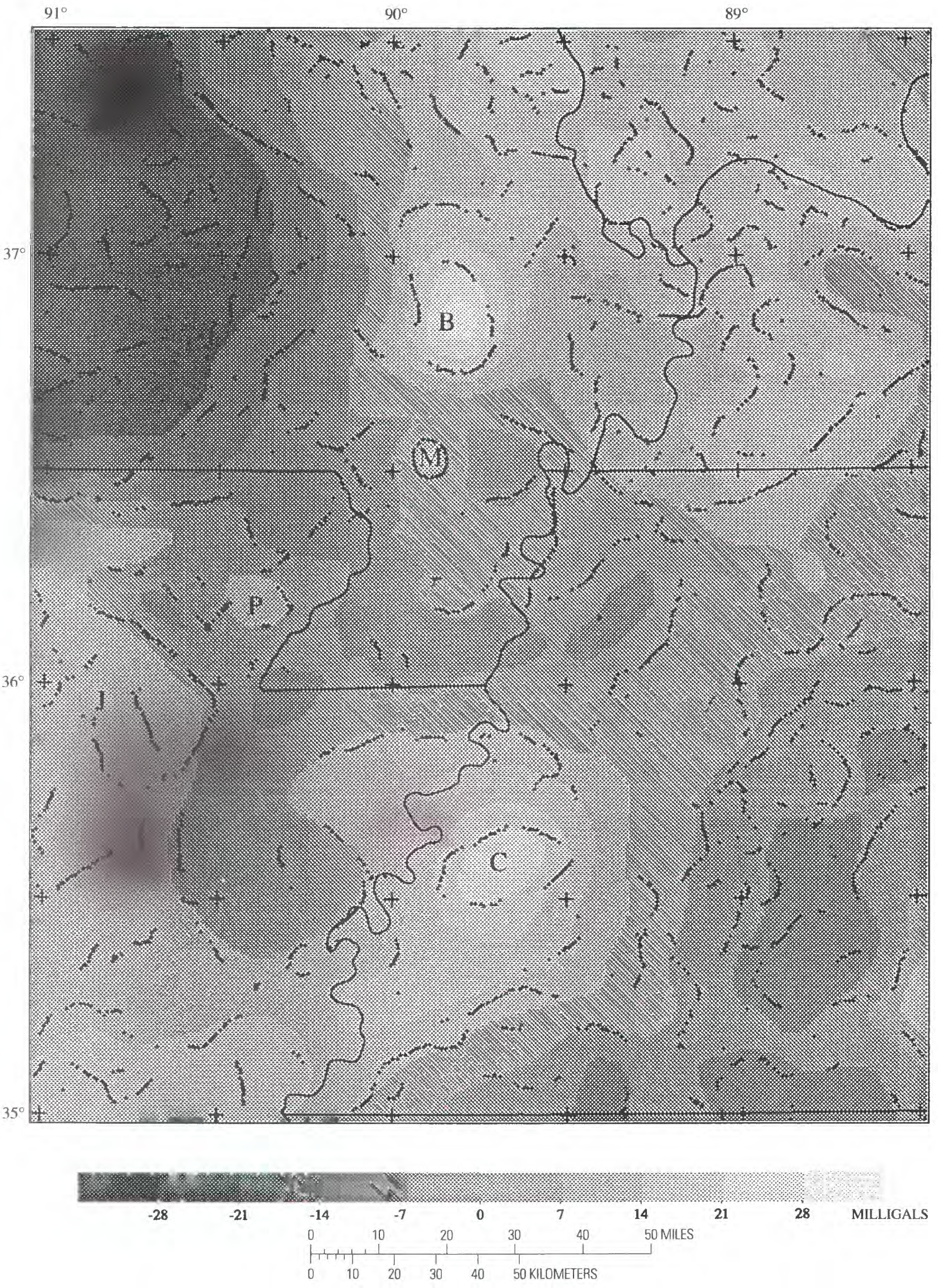


Figure 5. Gravity map of the northern Mississippi Embayment continued upward to an altitude of 3 km. Contour interval is 5 mGal. Dots indicate positions of maximum horizontal gravity gradient. B, Bloomfield pluton; C, Covington pluton; J, Jonesboro pluton; M, Malden pluton; P, Paragould pluton. Anomalies reflect long-wavelength component of gravity field and thus reflect sources with considerable vertical extent. State boundaries are shown as solid lines.

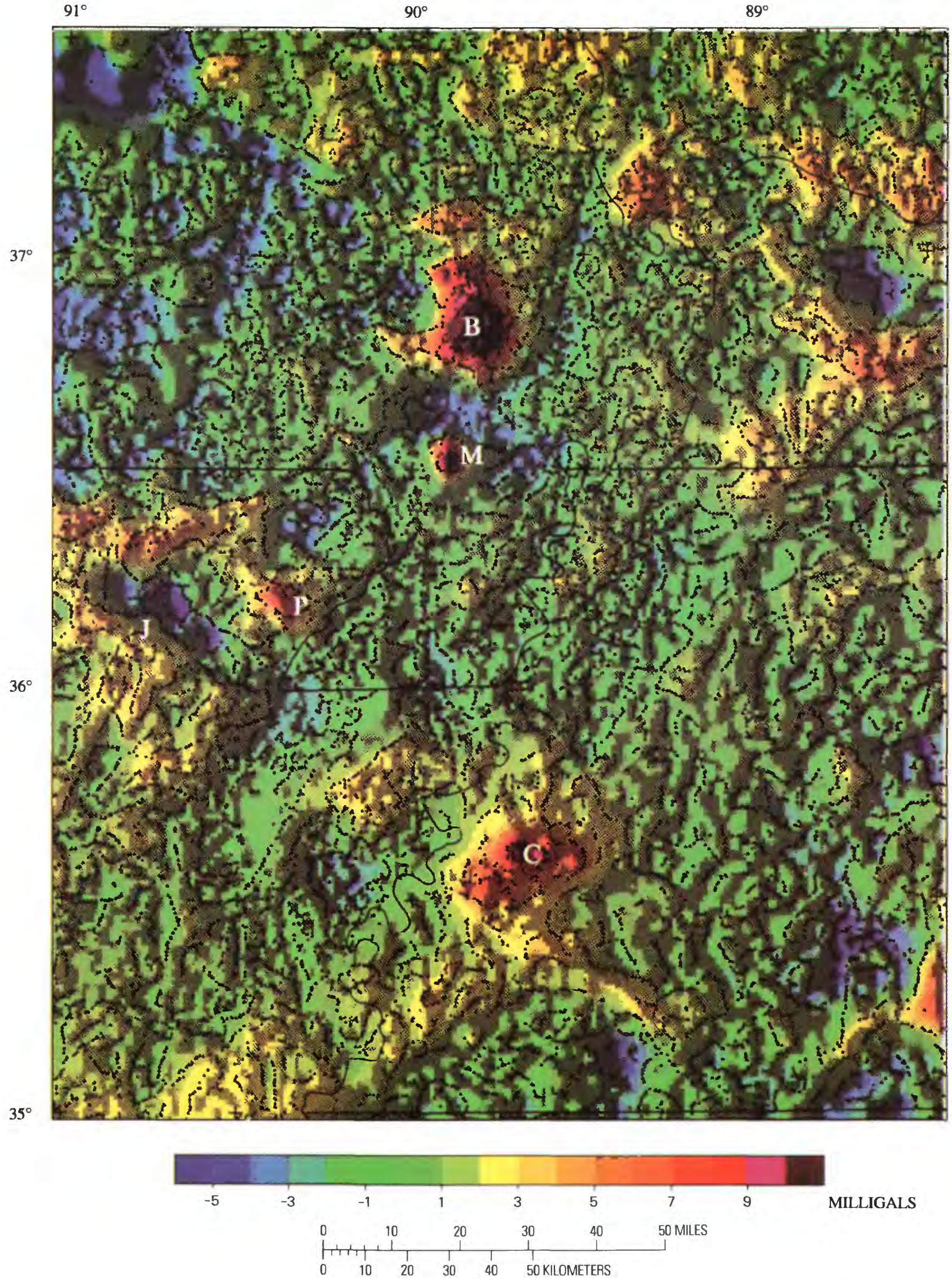


Figure 6. Shaded-relief map of residual gravity of the northern Mississippi Embayment. Residual gravity field is obtained by subtracting gravity field upward-continued to 3 km from the complete Bouguer gravity field. Illumination is from the west. Anomalies reflect short-wavelength component of gravity field and thus emphasize shallow gravity sources. Contour interval is 1 mGal. Dots indicate positions of maximum horizontal gravity gradient. B, Bloomfield pluton; C, Covington pluton; J, Jonesboro pluton; M, Malden pluton; P, Paragould pluton. State boundaries are shown as solid lines.

GEOPHYSICAL FEATURES

REGIONAL GRAVITY

Bouguer gravity values range from –50 mGal in the northwestern part of the map (over the low-density St. Francois Mountains, a 1.2- to 1.5-Ga rhyolitic and granitic terrane (Bickford and others, 1981)) to almost 40 mGal in the north-central part of the map (fig. 2). Rocks in the St. Francois Mountains have an apparent average density of 2.67 g/cm^3. The largest positive gravity anomalies occur over the unconsolidated sediments of the Mississippi Embayment and coincide with high-amplitude magnetic anomalies (fig. 4). The causative bodies are considered to be dense, highly magnetic mafic plutons that are as shallow as 1.5 to 3.0 km below the ground surface (Hildenbrand and others, 1982; Ravat and others, 1987). Only one such anomaly has been drilled: a well near the Covington pluton in southwestern Tennessee (fig. 7) encountered nepheline syenite directly beneath Upper Cretaceous sedimentary rocks (Kidwell, 1951); the age of the pluton can only be constrained as post-Ordovician and pre-Late Cretaceous. A prominent northwest-trending gravity low extending from the northwest corner of the map (fig. 2) is the Missouri gravity low, which Guinness and others (1982) interpreted as the expression of a Precambrian rift and which Hildenbrand and Hendricks (chapter E, this series) interpret as a batholith. It intersects a somewhat more subdued, northeast-trending gravity trough in the center of the map (fig. 2). This northeast-trending feature is the gravity expression of the Reelfoot graben, which is more strikingly imaged by the magnetic anomaly map and pseudomagnetic and residual-gravity-anomaly maps (compare fig. 1 with figs. 3, 4, and 6). Most of the seismicity in the New Madrid seismic zone occurs within the area at the intersection of the two gravity lows (Guinness and others, 1982; Hildenbrand and Hendricks, chapter E, this series; compare figs. 1 and 2). The gravity field within the Reelfoot graben is relatively nondescript, but several northeast-trending gravity highs with amplitudes of 5 to 15 mGal are present along the axis of the graben (fig. 2). These gravity highs coincide geographically with magnetic highs, suggesting that the causative bodies are buried igneous intrusions of intermediate to mafic composition.

The pseudomagnetic and residual gravity fields (figs. 3 and 6) more closely resemble the magnetic field. For example, the Covington pluton is a broad (more than 50 km wide), somewhat blocky high on the unfiltered gravity. On the filtered gravity maps (figs. 3 and 6), this broad high separates into two to three isolated anomalies; the central high most closely resembles the magnetic anomaly of the Covington pluton, a small anomaly elongated in both east-west and northeast-southwest directions. The gravity high 25 km northwest of Covington still appears to be associated with the main anomaly, contrary to more completely separated anomalies on the magnetic map; the shape of this gravity high northwest of Covington, though, is more arcuate, as is the magnetic anomaly. Most of the gravity highs along the margins of the graben are characterized by blocky northeast- or northwest-trending edges (fig. 2), suggesting either that older structures provided pathways for ascending magmas or that younger faults have truncated pluton boundaries. Considering the long and complex geologic history of the Mississippi Embayment, the rising magmas that formed the plutons probably took advantage of older or contemporaneous zones of weakness within the crust. The Malden pluton (fig. 2) is an exception to the blocky texture of the gravity field; it is a circular, isolated, gravity high but is also smaller in size than the other major plutons.

Both northwest and northeast trends on the Bouguer gravity map are enhanced on the filtered-gravity-anomaly maps (figs. 3 and 6). Many of these trends are also present in the magnetic field, suggesting that these gradients reflect density and magnetic susceptibility boundaries in crystalline rocks (Precambrian basement rocks or igneous rocks of younger age). However, the pseudomagnetic map shows a 10- to 20-km-wide, discontinuous feature (X–X′, fig. 3) along the center of the Reelfoot graben that is not present on the magnetic map. This northeast-trending feature is also visible on the residual map (fig. 6) as a gravity high of 1–2 mGal. The southwestern part of the high corresponds geographically to the Blytheville arch and the Marked Tree–Caruthersville zone of earthquakes; the northeastern part of the high, separated from the southeastern trend by a gravity low, trends more northerly than does the zone of earthquakes and appears to be associated with a horseshoe-shaped magnetic anomaly (fig. 4). Thus, the source for the northeastern part of the high is most likely an igneous intrusion, whose linear edges, expressed in the gravity field, suggest faulting at shallow depths. The source for the southwestern part of the feature is essentially nonmagnetic; slightly denser sedimentary rocks forming the core of the anticlinal structure of the Blytheville arch could explain the presence of the narrow, discontinuous gravity high at the southwestern end of X–X′.

The largest amplitudes of horizontal gravity gradient occur along the boundaries of the plutons and over the northeastern part of the Reelfoot graben, where values reach 6 mGal/km. A comparison of the upward-continued and residual gravity fields shows that some features, such as the plutons and the southeastern graben boundary, contain both short- and long-wavelength components (figs. 5 and 6). Many other features, however, only appear on the residual map, implying that they do not extend to any great depth (i.e., more than a few kilometers). For example, most of the density boundaries within the graben are visible only on the residual map. The density boundaries derived from the residual gravity field are aligned along a predominantly northeasterly direction within the graben and along northwesterly directions in the area west of the graben.

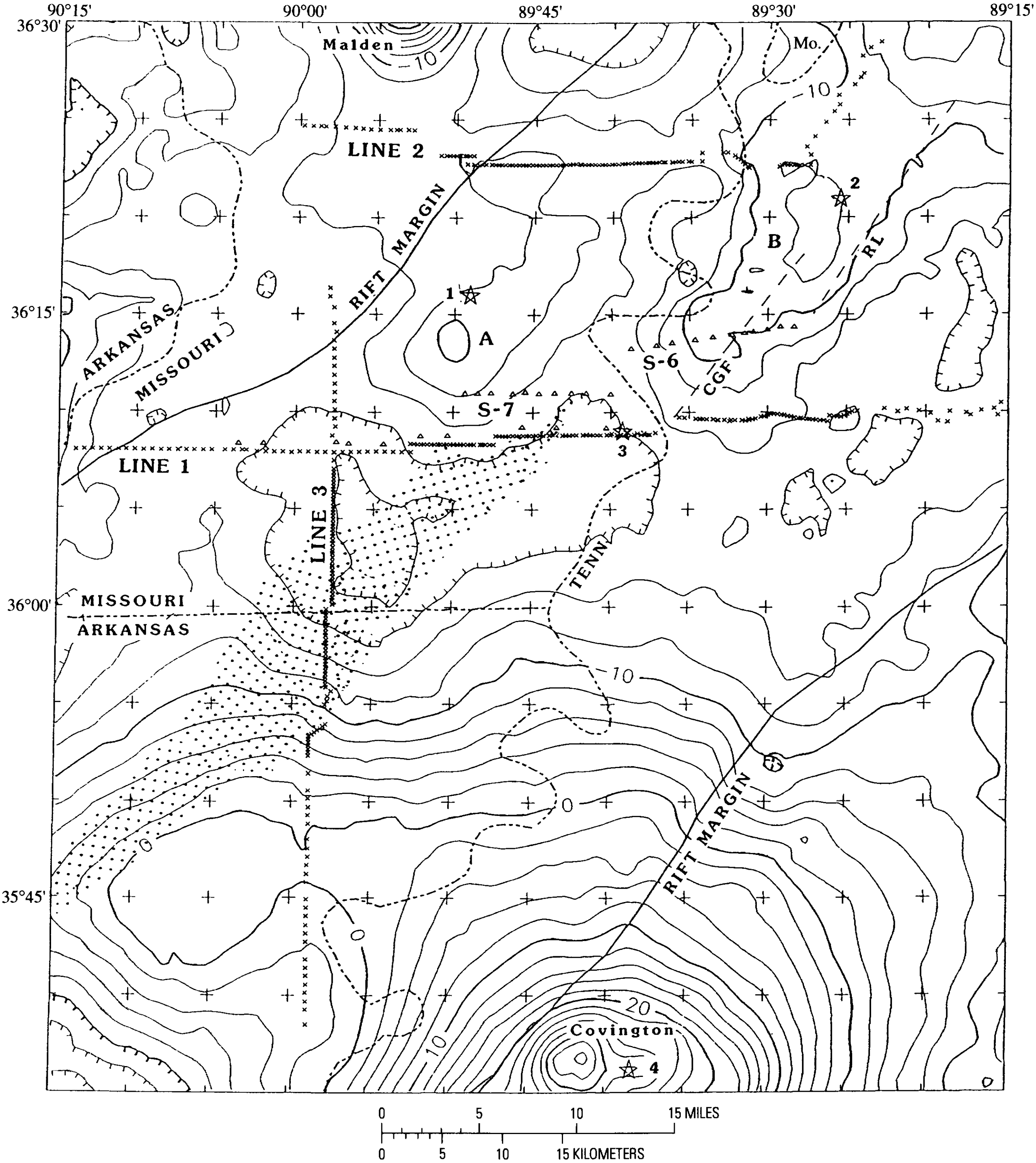


Figure 7. Complete Bouguer gravity map showing locations of detailed gravity profiles. Contour interval is 2 mGal. "x" indicates location of gravity measurement; star, location of selected well penetrating igneous rocks—see discussion in text (1, Strake Petroleum Incorporated, T.P. Russell No. 1; 2, Henderson Oil Markham No. 1; 3, O.W. Killiam, K. Pattinson No. 1 (Grohskopf, 1955); 4, Pure Oil Co. R.R. McGregor No. 1 (Dart, 1992)); triangle, selected seismic-reflection-profile shotpoint. Gravity profile of Sexton and Jones (1988) was conducted along the six easternmost shotpoints of seismic profile S-6. Stippled area outlines Blytheville arch. CGF, Cottonwood Grove fault; RL, Ridgely lineament. Anomalies A and B are also shown on figures 8 and 9.

Some of the northeast-trending boundaries occur in approximately the same location as faults that have been imaged on seismic reflection profiles. For example, density boundaries coincide with the Reelfoot fault and the Cottonwood Grove fault (Hamilton and Zoback, 1982). The magnitude of the horizontal gradient across these faults is relatively small, usually less than 1 mGal/km. Figure 1 shows selected density boundaries digitized from the residual gravity map; these boundaries were chosen only where station coverage was adequate for determining the locations of the horizontal gravity gradients. Pluton boundaries were derived from a combination of residual and upward-continued density boundaries (fig. 1). The significance of these boundaries is discussed later.

DETAILED GRAVITY PROFILES

Three profiles collected by the U.S. Geological Survey were located to examine small-amplitude anomalies that might result from shallow structures in the New Madrid seismic zone (fig. 7). Line 1 (fig. 8*A*) is an 87-km-long, east-west line that crosses both the Marked Tree–Caruthersville and the Ridgely–New Madrid zones of seismicity. The westernmost gradient reflects the presence of the Paragould pluton (figs. 1, 8*A*). Although the magnitude of gravity variation is small along line 1 (less than 5 mGal), the abrupt changes in gradient indicate very shallow sources (at most about 1 km deep; anomalies A and B on figs. 8*A*, 9). The depth to the top of the Paleozoic rocks in this area ranges from 450 to 730 m, based on well and seismic data (Dart, 1992). Thus, the sources are possibly at or above the top of the Paleozoic section, which is Cambrian to Ordovician in age along line 1 (Grohskopf, 1955). Possible sources for these small-amplitude, high-frequency gravity anomalies include (1) lateral density variations within the post-Paleozoic sedimentary rocks, (2) the presence of small igneous intrusions, or (3) undulations or faulted offsets in the Paleozoic surface.

Lateral density variations within the post-Paleozoic sedimentary rocks may be related to low-density fill in ancient stream channels. Densities measured in well logs within the Cretaceous and Cenozoic sedimentary sequence range from 1.42 to 2.65 g/cm^3 (Crone and Russ, 1979). Sexton and Jones (1988) imaged Eocene stream channels on high-resolution seismic reflection lines and modeled the gravitational effects of the fill using a density contrast of 0.10 g/cm^3 to fit the observed gravity field. Thus, density contrasts exist within the post-Paleozoic section that could cause small-amplitude and small-wavelength anomalies. In the particular case of line 1, the widths of anomalies A and B (greater than 10 km) are larger than those of very wide stream channels, implying a non-fluvial source for the anomalies. The gravity anomalies are the southernmost expression of two regional gravity anomalies that have straight, northeast-trending edges that are about 20 km in length (fig. 7); such long, straight edges for stream channels seem improbable. The gravity anomalies also appear to be spatially related to magnetic anomalies (fig. 8*A*), which is suggestive of an igneous origin. Thus, it seems unlikely that the cause of the gravity anomalies on line 1 is lateral density variations associated with stream channels within Cretaceous-Cenozoic sedimentary rocks, although channel-fill deposits are potential candidate sources for gravity anomalies on other profiles.

The second possibility, small igneous intrusions, is certainly intriguing in that such intrusions, at depths of less than 1 km (and thus possibly younger than the Cretaceous unconformity) could suggest Tertiary igneous activity within the Mississippi Embayment. A Tertiary igneous event has been inferred from on the basis of deformation of shallow reflectors (Zoback and others, 1980) and from doming of pre-Eocene sediments over a pluton along the graben margin (Glick, 1982). However, if igneous rock intrudes only the Paleozoic rocks, the age of the intrusion is only constrained as post-Middle Ordovician. In the case of the anomalies on line 1, the spatial relationship of the gravity and magnetic anomalies would support this interpretation of a pluton intruding at least the Paleozoic rocks. However, the magnetic signature along line 1 does not reveal the high-frequency anomaly expected for a magnetic body at depths of about 1 km. Instead, the magnetic gradients indicate maximum depths of 2 to 3 km; such depths would place the intrusion entirely within Paleozoic sedimentary rocks or at the top of the Precambrian basement in this area. A seismic reflection line along the western two-thirds of line 1 (west of the Mississippi River) does image disrupted and arched reflections in the area of anomaly A, which have been interpreted as an intrusion at depths of about 1.5 km (F.A. McKeown, written commun., 1992). Superimposed on anomaly B are two very small anomalies of about 0.5 mGal, which correspond in location to very small magnetic anomalies of about 6–8 nT (arrows on fig. 8*A*). These features could be caused by small dikes at very shallow depths. Part of the magnitude of the gravity anomalies on line 1 is caused by igneous intrusions, but this source alone cannot explain both the magnetic and gravity signature of the anomalies.

The third possible explanation of the source of the high-frequency gravity anomalies is undulations or vertical offsets in the unconformity on the Paleozoic rocks. A substantial average density contrast of about 0.5 g/cm^3 exists between the Paleozoic rocks (average density about 2.7 g/cm^3) and the post-Paleozoic sedimentary rocks (average density of about 2.2 g/cm^3). Crone and Brockman (1982) have argued that little topographic relief on Paleozoic bedrock existed by Late Cretaceous time, based on geologic considerations and seismic reflection data. Seismic line S-6, which is parallel to but about 8 km north of the eastern part

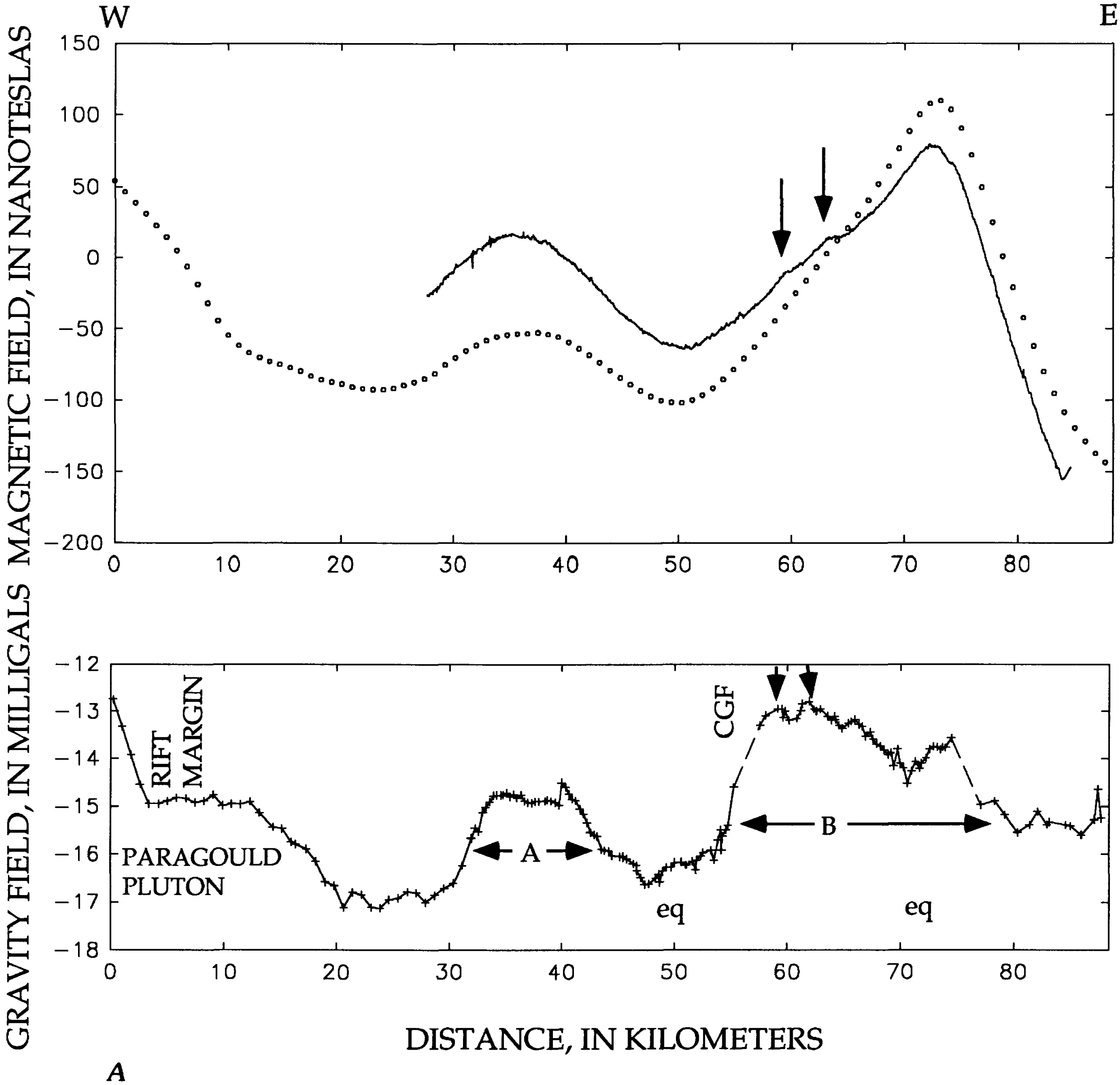
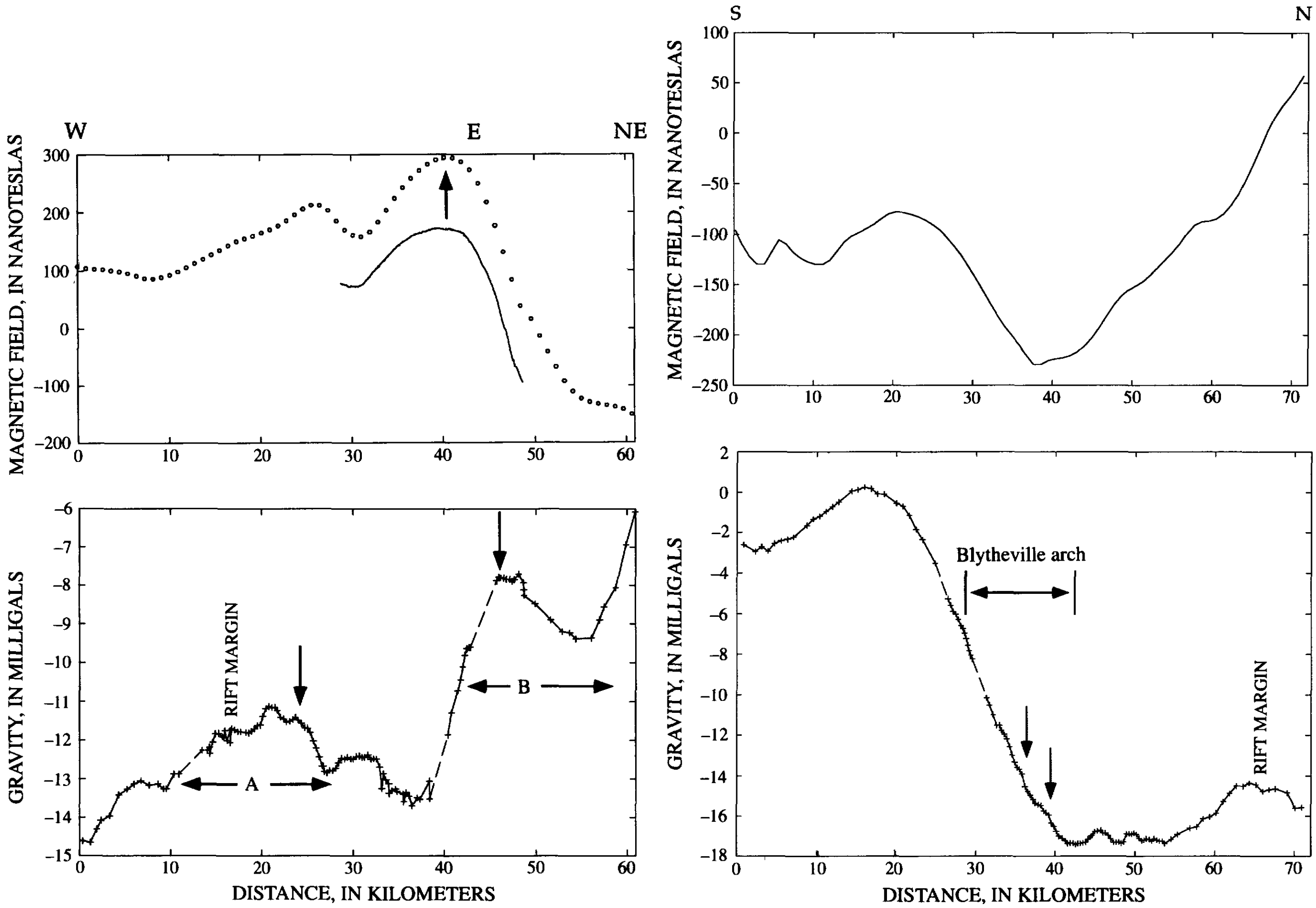


Figure 8 (above and facing page). Locations of gravity-profile lines 1, 2, and 3 are shown in figure 7. *A*, Gravity and magnetic-field profile along line 1. Cross indicates gravity measurement; circle, gridded magnetic-field point; line on magnetic profile, data along flight line at 90-m altitude. Gridded data have not been adjusted relative to the arbitrary datum of flight-line data. Anomalies A and B are discussed in text as bounded by gradients that indicate sources at depths of less than 1 km. Dashed lines between gravity measurements indicate offset or gap in sampling. CGF shows the projection of the Cottonwood Grove fault onto line 1, and "eq" indicates where line 1 crosses zones of seismicity. Arrows point to small-amplitude, short-wavelength anomalies that may indicate buried igneous dikes. *B*, Gravity and magnetic-field profile along line 2. Cross indicates gravity measurement; circle, gridded magnetic-field point; solid line on magnetic profile, data along flight line at 90-m altitude. Gridded data have not been adjusted relative to the flight-line data. Gravity and magnetic profiles projected onto east-west line that bends to the northeast at about 47 km. Arrows indicate coincident magnetic and gravity anomalies that may indicate buried igneous bodies. *C*, Gravity and magnetic-field profile along line 3. Cross indicates gravity measurement. Magnetic-field data from grid. Gravity and magnetic high on southern part of profile indicates an igneous intrusion that may be associated with the Covington pluton. Arrows point out small inflections on gradient that may reflect the presence of faults, igneous bodies, or stream channels.



B *C*

of line 1, images the Cottonwood Grove fault (CGF) at the approximate location of anomaly B (Zoback and others, 1980; Hamilton and Zoback, 1982). The amount of vertical offset on the CGF is about 80 m. Using the infinite Bouguer slab approximation, the maximum gravity anomaly resulting from an 80-m offset of the Cretaceous unconformity (and assuming a density contrast of 0.5 g/cm^3) would be about 1.7 mGal, which is about half of the 3 mGal anomaly observed on line 1 (fig. 8A). The maximum amount of offset predicted from gravity data is thus about 160 m, double that imaged on the seismic reflection line. Seismic line S-7 images another small fault with an offset of 20 m, that lies along trend with anomaly A (Hamilton and Zoback, 1982); the predicted offset from the gravity data is about 100 m.

The discrepancy between the fault-offset estimates may disappear when one considers the gap in sampling at the exact location of the CGF and that igneous intrusions are present beneath line 1. Both anomalies A and B are located on the southernmost tip of two regional gravity highs (fig. 7) and their corresponding regional magnetic highs. For this reason, the two-dimensional model in figure 9 is an oversimplification because the anomalies are clearly three-dimensional in nature. Nonetheless, all of the lower amplitude gravity anomalies have sources no deeper, and probably shallower, than the body producing anomaly A. Although the character of the anomalies along line 1 indicate shallow depths, both the regional gravity and magnetic anomalies imply deeper sources that are probably igneous intrusions. Three drill holes intersect mica peridotite and lamprophyric dikes at depths of less than 1 km in the area of line 1 (fig. 7; Grohskopf, 1955); one of these dikes has been dated as Permian in age (Zartman, 1977). These dikes could be associated with largér intrusions at depth. The magnitude of anomalies A and B may thus be a combination of both deeper igneous bodies and shallower faults. Hamilton and Zoback (1982) suggested that shallow faults may be related to igneous intrusions at depth. Zoback and others (1980) interpreted arched reflectors below the Paleozoic–Upper Cretaceous unconformity on seismic line S-6 as evidence of possible shallow intrusions (depths of about 1–2 km), but a detailed gravity profile directly over the eastern half of seismic line S-6 does not indicate a subsurface density contrast that would be expected from such a body (Sexton and Jones, 1988). Unfortunately, this detailed gravity profile is short (5 km) and obliquely crosses the gravity feature (fig. 7), but it does show a small gravity step associated with the CGF. In summary, the abrupt changes in gradient along line 1 indicate sources at 1-km depth that could be caused by

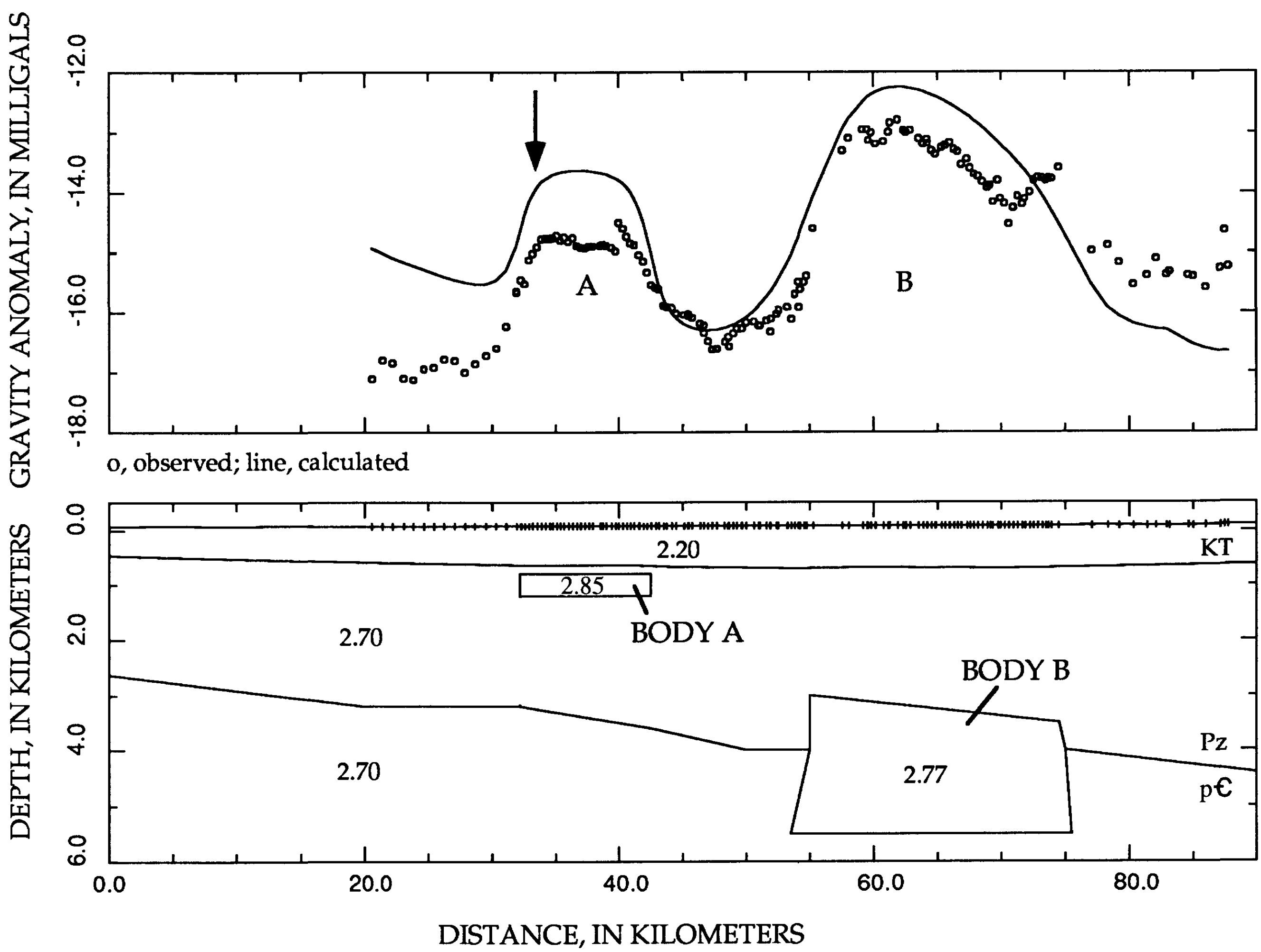


Figure 9. Simple two-dimensional model of gravity data across anomalies A and B on line 1. KT refers to Cretaceous and Tertiary sedimentary rocks; Pz, Paleozoic sedimentary rocks; p€, Precambrian crystalline basement. Control on depth of Paleozoic-Precambrian contact from maximum depths to magnetic basement (Hildenbrand and others, 1979); control on depth of Paleozoic-Cretaceous unconformity taken from gridded drill-hole data and seismic reflection data (Dart, 1992). Numbers within model are densities in grams per cubic centimeter (g/cm^3). The model is oversimplified in that anomalies A and B are the southernmost tips of a pair of three-dimensional anomalies. Source of A must be shallower than 1 km in order to match abrupt changes in gradient bounding anomaly A (shown by arrow). All the smaller and more abrupt gravity features have sources no deeper, and probably shallower, than body A.

either (1) faults offsetting the Paleozoic surface possibly related to deeper igneous intrusions, (2) shallow intrusions, or (3) both, especially because the CGF seems to correlate with the edge of a gravity high.

Line 2, the northernmost profile, trends east-west for most of its length, but bends abruptly to the northeast at its eastern end, skirting the southern flank of the Malden pluton (fig. 7). The profile shows several small-amplitude gravity anomalies (fig. 8*B*). The total variation in gravity values is about 9 mGal along the 56-km-long profile. The western part of the profile crosses the northern tip of anomaly A (fig. 7), which is expressed here by a broad 3- to 4-mGal anomaly. Superimposed on this gentle high are smaller anomalies (less than 1 mGal), some of which have relatively abrupt gradients. These smaller anomalies may be caused by stream channels, small faults, or small igneous intrusions. Because little seismic reflection data are available in this area and high-resolution aeromagnetic data cover only the eastern half of line 2, it is difficult to determine whether these anomalies are caused by igneous rock. Nonetheless, two anomalies on the gridded magnetic data coincide somewhat with the gravity signature, suggesting that these gravity features are caused by possible igneous intrusions (arrows on fig. 8*B*).

Line 3, a north-south profile measured along a proprietary seismic reflection line that crosses the Blytheville arch, shows a large gravity high at its southern end (fig. 8*C*). The 3-mGal high on the northern part of the profile is the southwesternmost tip of anomaly A (fig. 7). The major gravity high at the southern end of line 3 corresponds geographically with a magnetic high of about 50 nT, which probably indicates the existence of an igneous body at depth. The northern gradient of this gravity high coincides with the location of the Blytheville arch. The steep, fairly uniform northern gradient of the anomaly suggests that no significant lateral density contrast exists between the zone of incoherent reflected energy that characterizes the arch and the coherent, generally undeformed strata of the adjacent Paleozoic rock. These results are consistent with previous work that suggested no gravity expression of the Blytheville arch (Crone and others, 1985). However, small inflections in the gravity field are present along line 3; these small-amplitude (less than 1 mGal) gravity anomalies along line 3 may indicate small offsets on post-Cretaceous faults, small igneous intrusions, or density variations within the Cretaceous and Tertiary sedimentary deposits. Some of the small inflections in the magnetic anomalies may not be real but instead may be artifacts resulting from small datum shifts between the east-west flight lines used to create the gridded data; these small changes do not correlate well with small gravity anomalies (fig. 8*C*), suggesting that small igneous bodies are not a likely source for the gravity anomalies. Although the disrupted zone in the Paleozoic rocks in the arch is blanketed by Cretaceous sedimentary rock (Crone and others, 1985), and McKeown and others (1990) argue that the arch formed by shale diapirism between Pennsylvanian or Permian and Late Cretaceous time, present-day seismicity appears to correlate with the location of the Blytheville arch. The small gravity anomalies on line 3 may be caused by small, vertical offsets on faults caused by reactivation of deeper, older structures associated with the arch; these faults may be continuous, as suggested by density boundaries calculated on residual gravity anomalies. These density boundaries correlate with and are parallel to a 20- to 25-km segment of the southern part of the Blytheville arch (fig. 1).

DISCUSSION

All three detailed gravity profiles show relatively flat gravity fields within the Reelfoot graben, except where the profiles cross inferred igneous intrusions. Nonetheless, small-amplitude, short-wavelength gravity anomalies indicate shallow masses of relatively dense rock within the Reelfoot graben. Some of these anomalies could be caused by small igneous intrusions because the gravity features coincide with very small magnetic features. Other gravity anomalies could be caused by small vertical displacements on faults that offset the Cretaceous unconformity, such as along line 1. Other anomalies could be caused by ancient stream channels, that is, very near surface density contrasts, but additional data are needed to demonstrate this possibility. These profiles demonstrate that the gravity method, in conjunction with other geophysical and geologic data, can be an important tool in delineating shallow features and determining their structural significance with respect to the cause and distribution of earthquakes in the Mississippi Embayment.

The residual gravity field images shallow gravity sources. The accuracy of this statement depends greatly on the assumption that long-wavelength features are the result of deeply buried bodies. However, shallow bodies are capable of generating long-wavelength anomalies, given the non-uniqueness of potential-field data; a thin sheet near the surface (if characterized by a complex density distribution) may produce an anomaly similar to that of an equidimensional object at depth. As a result, some shallow, broad structures may not appear on the residual map. Nonetheless, narrow fault zones that displace shallow horizons should be visible on the residual map.

The maximum-horizontal-gradient method should be successful in locating faults that offset the Paleozoic-Cretaceous unconformity. The method fails in circumstances where the gravity source is characterized by gently dipping sides or non-uniform densities. Most of the faults imaged by seismic reflection techniques (Zoback and others, 1980; Hamilton and Zoback, 1982; Sexton and Jones, 1986) dip steeply, and, therefore, the locations of these faults will be adequately located by the maximum-horizontal-gravity-gradient method if the faults juxtapose rocks of different densities. A large density contrast exists between the Cretaceous and Tertiary sedimentary rocks (average density of about 2.20 g/cm^3) and the Paleozoic sedimentary rocks (densities ranging between 2.40 to 2.80 g/cm^3, averaging about 2.70 g/cm^3). Assuming a density contrast of 0.50 g/cm^3 and an infinite Bouguer slab, the maximum gravity anomaly associated with this unconformity is estimated to be 0.02 mGal per meter of vertical fault offset. If this typically flat unconformity is offset by only 50 m, a detectable gravity anomaly of 1 mGal would result. Because the density of Paleozoic sedimentary rocks is slightly less than or comparable to the density of the Precambrian basement (densities ranging from 2.60 to 2.75 g/cm^3), the gravity method will probably be of limited use in locating deeper faults that offset Paleozoic and basement rocks.

The maximum-horizontal-gravity-gradient method can locate possible fault offsets within the embayment. The horizontal displacement of a gradient maximum from the top edge of an offset horizontal layer is always less than or equal to the depth to the top of the source for moderate to steep dips (45° to vertical; Grauch and Cordell, 1987). Thus, for faults that offset the Cretaceous unconformity within the northern Mississippi Embayment, where the thickness of Cretaceous and Tertiary sedimentary deposits rarely exceeds 1 km (Dart, 1992), the maximum location error is on the order of 1 km.

The maximum-horizontal-gravity-gradient method also assumes that gravity sources are characterized by homogeneous densities. However, drill-hole data show that the Covington pluton violates this assumption because gravity data indicate the pluton is composed of dense rock (Hildenbrand and others, 1982), yet the top of the pluton is composed of low-density nepheline syenite. The maximum horizontal gravity gradients outlining the extent of the pluton may delineate density variations within the pluton or abrupt changes in depth of burial. For this reason, more than one boundary may be necessary to delineate the areal extent of the buried plutons (fig. 1). In addition, the wide range of densities present within the Cretaceous and Tertiary sedimentary rocks means that some of the density boundaries that are interpreted as possible faults may be the edges of stream-channel deposits. Anomaly linearity, amplitude, and width may help to distinguish between anomalies caused by faulting or stream fill.

The gravity field over the northern Mississippi Embayment does not reveal any large gravity anomalies within the boundaries of the Reelfoot graben except over major igneous intrusions that are inferred from associated gravity and magnetic anomalies. The absence of large gravity anomalies within the graben provides a maximum limit to the amount of vertical displacement on faults that offset the Palozoic-Cretaceous unconformity. For example, a vertical offset of 1 km on the unconformity would produce an estimated maximum gravity anomaly of 21 mGal. On the residual gravity map, the maximum amplitude of gravity highs present within the graben ranges between 3 to 5 mGal (fig. 6), which corresponds to vertical offsets of about 140 to 240 m on the Cretaceous unconformity. Large, post-Cretaceous offsets are expected because of the large-magnitude 1811–12 earthquakes and the well-defined zones of seismicity. One explanation for the lack of large vertical offsets is the alternative of right-lateral strike-slip motion similar to that based on focal mechanisms for earthquakes along the graben's axis. This right-lateral shear is consistent with studies showing that the regional stress field is dominated by east-west compression, which would produce lateral slip on the northeast-trending structures in the northern Mississippi Embayment (Zoback and Zoback, 1981). The present orientation of the stress field may be old, perhaps dating back to the beginning of rifting along the eastern North American margin during the Jurassic and Cretaceous. The cumulative amount of right-lateral motion is not known, although gravity and magnetic data do not indicate any significant right-lateral motion (greater than about 10 km) that disrupts the continuation of the Missouri gravity low or other northwest-trending geophysical features across the Reelfoot graben. Perhaps the activation of these faults is very episodic. Zoback and Zoback (1981) identified several intraplate regions that are characterized by long periods of quiescence separated by large historical earthquakes. Trenching in the Reelfoot Lake area suggests that recurrence times for large earthquakes are on the order of 600–1,000 years and that most of the uplift seen along the northwest-trending zone of seismicity occurred during the last 2,000 years (Russ, 1982). Schweig and Marple (1991) have also suggested that the 1811–12 earthquakes occurred along different planes of weakness than those outlined by current seismicity. Another, less likely, possible explanation for small vertical offsets is that the amount of energy released by the Mississippi Embayment earthquakes has been overestimated because of the lack of attenuation of seismic waves through old, competent Precambrian crust. Nonetheless, the maximum-horizontal-gravity-gradient method can locate density boundaries that coincide geographically with faults imaged by seismic reflection data. Thus, inexpensive gravity data can help pinpoint potential faults that warrant further investigation by other more expensive geophysical data.

CONCLUSIONS

Despite well-defined linear zones of seismicity and the occurrence of large historical earthquakes in the New Madrid seismic zone, the analysis of the gravity field indicates that, in general, faults here are not characterized by major vertical offsets, confirming the results of previous, more localized, seismic reflection work. Because of the large density contrast between the Paleozoic rocks and overlying Cretaceous and Tertiary sedimentary rocks, any offset of this unconformity would produce a gravity anomaly of significant magnitude; such anomalies are not found. In the northern Mississippi Embayment, where the thickness of post-Paleozoic rocks ranges from near zero to about 1 km, the change in gradient that results from a vertical offset of the Paleozoic-Cretaceous unconformity would also be abrupt and local because of the shallow depth of burial. Three detailed gravity profiles in the Reelfoot graben show unexpected local variation in gravity values and identify small-amplitude anomalies characterized by abrupt changes in gradient. These anomalies may be caused by either small igneous intrusions (where the anomalies correlate with small magnetic anomalies) or post-unconformity faulting. Gravity data filtered to enhance short-wavelength features reveal the locations of density contrasts that correspond to known subsurface faults cutting the Cretaceous unconformity. The method of analyzing maximum horizontal gravity gradients can be used to define the extent of faults imaged on seismic reflection profiles—the method thus provides important information that will contribute to better seismic risk assessments, such as the amount of post-Cretaceous offset and the lengths of faults.

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